NGA GPS Monitor Station
High-Performance Cesium Frequency Standard Stability: From NGA Kalman Filter Clock Estimates

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Abstract

The National Geospatial-Intelligence Agency (NGA) operates a worldwide network of GPS monitoring stations that utilizes high-performance cesium frequency standards (CFS) and geodetic quality GPS receivers. The NGA Monitor Station Network (MSN) has been in operation for almost 20 years and has recently moved to a 24/7 operation. The NGA monitor station CFS are located in non-laboratory environments and in some instances, are logistically challenging. With the onset of the Department of Defense GPS Accuracy Improvement Initiative (Aii), the NGA monitor station cesiums, along with the associative electronics, must be monitored more frequently for quality control. Aii involves the Air Force Operational Control Segment (OCS), at Schriever AFB, to incorporate a subset of the NGA monitor stations in real-time processing to improve the quality of the broadcast ephemeris and clock parameters. The addition of these stations will also expand the network coverage to allow all GPS satellites to be monitored without any gaps.

This paper is a summary of the stability of the NGA MSN cesiums using one year (52 weeks) of Kalman Filter clock estimate data computed daily at the NGA facility in St. Louis. The quality of the CFSs to be shown and summarized in this report is from eleven NGA monitor stations, which are to be added to the OCS estimation process under Aii. Results show that the NGA configuration of CFS has maintained the industry standards for high performance cesiums. This gives the NGA GPS program some of the most reliable monitor station clock data to support current and future GPS navigation systems.

Introduction

Today, the National Geospatial-Intelligence Agency (NGA) operates a globally distributed network of eleven automated GPS monitor stations. The primary mission of the Monitor Station Network Control Center (MSNCC) is to collect observations from the GPS constellation. These observations, in conjunction with observations provided by the GPS Operational Control Segment (OCS) and three International GNSS Service (IGS) stations, are used to compute the NGA precise ephemeris and clock information for all the GPS satellites. Currently, the eleven NGA monitor stations are located in: Adelaide, Australia; Buenos Aires, Argentina; Hermitage, England; Manama, Bahrain; Quito, Ecuador; Washington, D.C.; Fairbanks, Alaska; Wellington, New Zealand; Pretoria, South Africa; Osan, South Korea; and Papeete, Tahiti. There are an additional two station that are currently used for testing, evaluation, and training. The St. Louis, Missouri and Austin, Texas stations do not usually contribute to the precise ephemeris production. All NGA monitor stations, with the exception of the United States Naval Observatory (USNO), are outside of the Continental United States. The first six NGA stations, listed above, are to be used in the Department of Defense (DoD) Accuracy Improvement Initiative (Aii) starting in the summer of 2005 **[1]**. Adding the six NGA stations with the six OCS stations to the Aii process will improve the satellite-monitoring capabilities to 100% dual coverage. The OCS Master Control Station (MCS), at Schriever AFB, which processes the ranging measurements in a Kalman filter every 15 minutes, will incorporate the GPS satellite tracking data, to be supplied by the NGA monitor stations. The addition of the NGA data will be used to improve the quality of the broadcast ephemeris and clock parameters **[1,2]**. The five remaining NGA monitor stations are scheduled for a 24-hour communications upgrade by the end of the year 2005 and added to the Aii process by the spring of 2006. Adding all eleven NGA stations has shown to improve satellite-monitoring capabilities from 97% single-station coverage to continuous 100%, triple-station monitoring of all satellites **[3]**.

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14. ABSTRACT
The National Geospatial-Intelligence Agency (NGA) operates a worldwide network of GPS monitoring stations that utilizes high-performance cesium frequency standards (CFS) and geodetic quality GPS receivers. The NGA Monitor Station Network (MSN) has been in operation for almost 20 years and has recently moved to a 24/7 operation. The NGA monitor station CFS are located in non-laboratory environments and in some instances, are logistically challenging. With the onset of the Department of Defense GPS Accuracy Improvement Initiative (Aii), the NGA monitor station cesiums, along with the associative electronics, must be monitored more frequently for quality control. Aii involves the Air Force Operational Control Segment (OCS), at Schriever AFB, to incorporate a subset of the NGA monitor stations in real-time processing to improve the quality of the broadcast ephemeris and clock parameters. The addition of these stations will also expand the network coverage to allow all GPS satellites to be monitored without any gaps. This paper is a summary of the stability of the NGA MSN cesiums using one year (52 weeks) of Kalman Filter clock estimate data computed daily at the NGA facility in St. Louis. The quality of the CFSs to be shown and summarized in this report is from eleven NGA monitor stations, which are to be added to the OCS estimation process under Aii. Results show that the NGA configuration of CFS has maintained the industry standards for high performance cesiums. This gives the NGA GPS program some of the most reliable monitor station clock data to support current and future GPS navigation systems.

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Each NGA monitor station, with the exception of USNO, incorporates a suite of electronics that includes two geodetic-quality GPS receivers (Ashtech Z(Y)-12) and two Agilent (formerly HP) 5071A cesium frequency standards (CFSs). The NGA monitor station at the USNO is tied to the USNO Hydrogen Maser ensemble DoD master clock. The CFS used at each station contains a high-performance cesium-beam tube **[4]**. Each CFS provides a five-megahertz (5Mhz) frequency reference to a GPS receiver. All station electronics including the CFS are rack-mounted in standard equipment racks and located in general office space. The deployment of equipment and personnel can be a complex task. NGA personnel, along with a technical contractor, travel to each location each year to foster diplomatic relations with the host organizations. They perform yearly maintenance and upgrades to the station, conduct training, and evaluate operational details for optimal performance.

The data used to determine frequency stability of the NGA CFSs is produced through a Kalman filter process. NGA produces both satellite and station clock offsets which are then adjusted to GPS time. This paper studies the NGA station clock stability to support the upcoming Aii program.

Kalman Filter (Adjusted) Clock Estimates

NGA produces daily Kalman Filter clock estimates using a suite of programs called OMNIS (Orbit Mensuration and Navigation Improvement Software). From **[5]**, "OMNIS is a system of programs designed to determine the orbits of several classes of satellites. Two different solution techniques are used: the method of batch least squares and the Kalman filtering/smoothing method. The batch least squares, referred to in this document as the Batch Processor, and is used to determine the orbits of the Transit and low altitude satellites. Kalman filtering/smoothing is used to determine the orbits of the Global Positioning System (GPS) satellites and/or certain host vehicle satellites and is referred to in this document as the GPS/Sequential (SEQ) Processor. The GPS/SEQ Processor can estimate parameters and covariances of many satellites at a time using data from numerous stations and/or satellite-to-satellite (SST) data. Additionally, GPS/SEQ Processor can be used to solve for station coordinate solutions. The Batch Processor is designed to solve for the parameters of one satellite using ground station data."

The clock estimates are derived via the OMNIS Kalman Filter/Satellite Adjust program. This program is used to adjust the NGA clock offsets to be consistent with GPS time. The GPS time system is one that is maintained by the OCS as part of their support to the GPS constellation, which in turn, produces the OCS clock estimates. The NGA clock offsets are derived relative to a 'master station', which is held fixed in the clock estimation process. The master station for NGA is usually the USNO clock ensemble, or occasionally, the alternate master clock (AMC) ensemble at Schriever AFB in Colorado. Both sites maintain an ensemble of hydrogen masers, which provides very stable frequency standards. Once the NGA clock estimates are adjusted to the OCS clock estimates, the resulting adjusted clock file is referred as the GPS satellite/station clock file. These are the final clock estimates, which is used for the final precise ephemeris provided by NGA.

The NGA clock offsets are adjusted to be consistent with GPS time through a sliding window technique. Satellite/Station clock differences between NGA offsets and OCS offsets are formed at 900-second (15 minute) time steps within a window centered on the time of interest. The time span is normally the middle day of a three-day fit. For each satellite/station at each 900-second, clock differences are formed. The average difference for each satellite/station is then formed over the entire window. The average of these values are then added to all NGA satellite/station offsets. This adjustment of the offsets makes them consistent with GPS time.

Frequency Stability Analysis

The analysis of the NGA Kalman filter clock estimate data, using Stable32, Stability Analysis Software **[6]**, is quite simple. The data-sampling rate is, as mentioned above, 900 seconds (15 minutes). The data read in is the phase offset. It is then scaled (multiplier) to E-06, i.e., NGA phase data is stored in microseconds. The phase offset is then converted to frequency offset. Now, by plotting the frequency data, outliers or any other oddity can be seen. In most cases, it is easier to visually examine frequency data vs. phase data. A linear frequency drift is then removed and residuals can be plotted. Then, an appropriate stability analysis statistic is performed. Since all NGA frequency standards are cesiums, the Allan Deviation is performed; moreover, the Overlapping Allan Deviation is preferred. This is due to the increased number of degrees of freedom and the improved confidence in the estimation

[7]. Additional editing and/or analysis, if necessary, can be performed at this time. The analysis consists of the relationship of frequency uncertainty to time (or phase) uncertainty.

Analysis of the frequency stability gives an indication on how well the frequency standards are performing. It also gives an idea of the types of noise that are generally inherent within the clocks and other environmental issues that could be introduced into the remaining electronic system. This includes temperature, pressure, and humidity extremes that could occur at each site. Two of the NGA stations have had special maintenance trips beyond the normal yearly maintenance trip for handling of environmental issues. Bahrain and South Korea are two stations that have required additional attention. Points of contacts (POC) at each station have also remained diligent.

This study looks at the Allan variance of the NGA monitor station data primarily to get an idea how the NGA CFS's are performing. This is used to help for any NGA maintenance related situations. The Hadamard/Allan variance data is used by the Air Force (MCS/OCS) to help in the 'fine-tuning' of their Kalman filter **[8,9]**. Numerous 'signal-in-space' studies have shown to improve navigation performance by the tuning of GPS clock estimates **[10]**. These also include current to future GPS programs **[11]**. The Naval Research Laboratory in the Washington DC performs more extensive work determining the GPS space vehicle clock offsets using NGA data **[12]**. This group uses data, both station and satellite, to aid in helping the MCS/OCS in the 'fine-tuning' of the Air Force Kalman filter.

Frequency Stability Analysis Figures

Figure 1 shows the frequency stability, from the NGA Kalman filter clock estimates, of the first six NGA monitor station CFS. This data set spans one year, which is arbitrarily GPS weeks 1260 to 1311. The vertical arrows on each plot indicate data at one-hour stability and at one-day stability. The first five plots, Australia through Ecuador (85402 through 85406) show the standard white frequency modulation (WFM) noise/characteristics found in the passive-resonator frequency standards, such as, the cesium's. Station 85405 (Bahrain) shows a 12-hour stability fluctuation, which causes rippling throughout the data. This is due to extremes in temperature differences throughout the day. NGA is currently working to correct the problems that are causing the temperature extremes that are affecting the operation of the station electronics. The station at the USNO (85407) shows the WFM at the one-hour stability then proceeds through flicker floor FM and then into random walk FM at the one-day stability. This characteristic is found in active hydrogen masers **[13]**.

Table 1 shows the frequency uncertainty to phase (time) uncertainty (values derived by NIST) and the NGA monitor station statistics for the time frame of this study. Although not shown, the frequency range for the first five (cesium) NGA stations is prominently $pp10^{13}$. The frequency range for the USNO master station (85407) is $pp10^{14}$ (not shown).

Figure 2 shows the frequency stability, from the NGA Kalman filter clock estimates, from the NGA monitor station in Fairbanks, Alaska. This station has been very reliable since it was established in the summer of 1998. But, 15 weeks into this study (GPS week 1274) receiver #1 failed causing a station outage for couple of hours. All NGA monitor stations, as mentioned above, are dual redundant, with receivers and cesium's connected in parallel. Therefore, with receiver #1 out, receiver #2 along with cesium #2 was activated. As one can see from the center frequency data plot, the data became noisier by about an order of magnitude. This was due to receiver #2 starting to fail. Within two weeks, both receivers were replaced and the new receiver #1 along with cesium #1 were reactivated. The frequency noise level has settled as can be seen by the associated frequency stability and frequency data plots. The Alaskan station has since returned to its very good reliability.

Figure 3 shows the frequency stability from the NGA New Zealand and South African augmentation monitor stations. From the New Zealand frequency data plot, about half way through the study, cesium #1 failed. The activation of cesium #2, along with receiver #2 was instantaneous. A before and after frequency stability plot is shown. The South African station has been a very reliable station. But, a couple of years back; it too had similar 12-hour stability fluctuations as the Bahrain monitor station due to temperature extremes. This only occurred on weekends and was due to a smaller auxiliary air conditioning unit in the monitor station not being able to handle the temperature extremes. The monitor station has been moved to a different location within the embassy and a more

powerful air conditioning unit has replaced the older unit. The electronics have since been secured and the South African monitor station has turned out to be one of the more reliable NGA stations.

Figure 4 shows the frequency stability from the NGA South Korea and Tahiti monitor stations. The South Korean station has been quite reliable since its establishment. But recent maintenance and frequent power outages at the location have caused some concerns where consistent monitoring of this station is necessary. The building where the equipment is housed is shared with another DoD contractor. Over the past year of this study this contractor has made numerous upgrades to their facility. This has caused disruptions in the station power, which in turn caused disruption with the air conditioning system. This caused the equipment to 'heat up' and therefore caused a disruption in the station monitoring availability. During the year of this study this station was shut down for about three to four weeks, two weeks at one stretch while maintenance continued. As can be seen from the frequency data plot, there is about 50 days where the frequency appeared more stable. The remaining time shows the frequency to appear to be less stable, or a little noisier. With the 50 days removed, the frequency stability plot labeled 'South Korea-up' shows the station still has a reliable stability, although at the one-day stability, the time uncertainty is at three nanoseconds (Figure 5). The final NGA monitor station, currently, is in Tahiti. The Tahiti monitor station, much like the South African station, has shown to be very reliable and stable. It is the newest NGA monitor station, being established in 2001.

Conclusion

To ensure the highest possible degree of accuracy, stability, and reliability, NGA monitors all eleven stations on a 24/7 operation. Yearly trips, sometimes sooner, are taken for both maintenance and administrative purposes. Within the next year to two years, each monitor station will be upgraded with dual AOA (now ITT) receivers, newer cabling, new antennas, and upgrades to the cesium frequency standards. Also, five of the monitor stations will be upgraded to get dedicated 24-hour communications. These five stations are also to be added to the Aii process at a later date (Fiscal Year 2006).

Extensive analysis of the GPS observation data is a daily procedure at NGA. This enables NGA to maintain the best possible orbit and clock precise ephemeris. Along with satellite clock evaluation, analysis of the NGA station CFS is also ongoing. Weekly NGA station CFS stability, along with monitoring the OCS station clock stability, via the daily NGA Kalman filter process is performed. This weekly analysis has helped with identifying possible problems and to help determine NGA monitor station quality. Results show that the NGA configuration of CFS has maintained the industry standards for high performance cesiums. For further detail, see 14, Chapter 6, Specifications. This gives the NGA GPS program some of the finest and most reliable monitor station clock data to support current and future GPS navigation systems.

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Table 1. The NGA monitor station statistics covering this study time period.

The Numbers*

Frequency Uncertainty	Measurement Period	Time Uncertainty
+/-2.78 x 10^{-13}	1-hour	+/-1 nsec
+/-1.16 x 10^{-14}	1-day	+/-1 nsec

*Courtesy of NIST **[15]**

NGA Monitor Station	Measurement Time 1-hour	1-day
85402 through 85406	0.3-0.5 nsec	2.0-2.5 nsec
85407	14 psec	0.8 nsec
85410 through 85414	0.4-0.6 nsec	1.8-2.9 nsec

Figure 5 shows the clock stability (frequency to time) of the NGA monitor stations 85402 through 85414. Stations 85402 through 85407 are to be added to the Aii process in the summer of 2005. Stations 85410 through 85414 are to be added to the Aii process sometime in the future, possibly spring 2006.

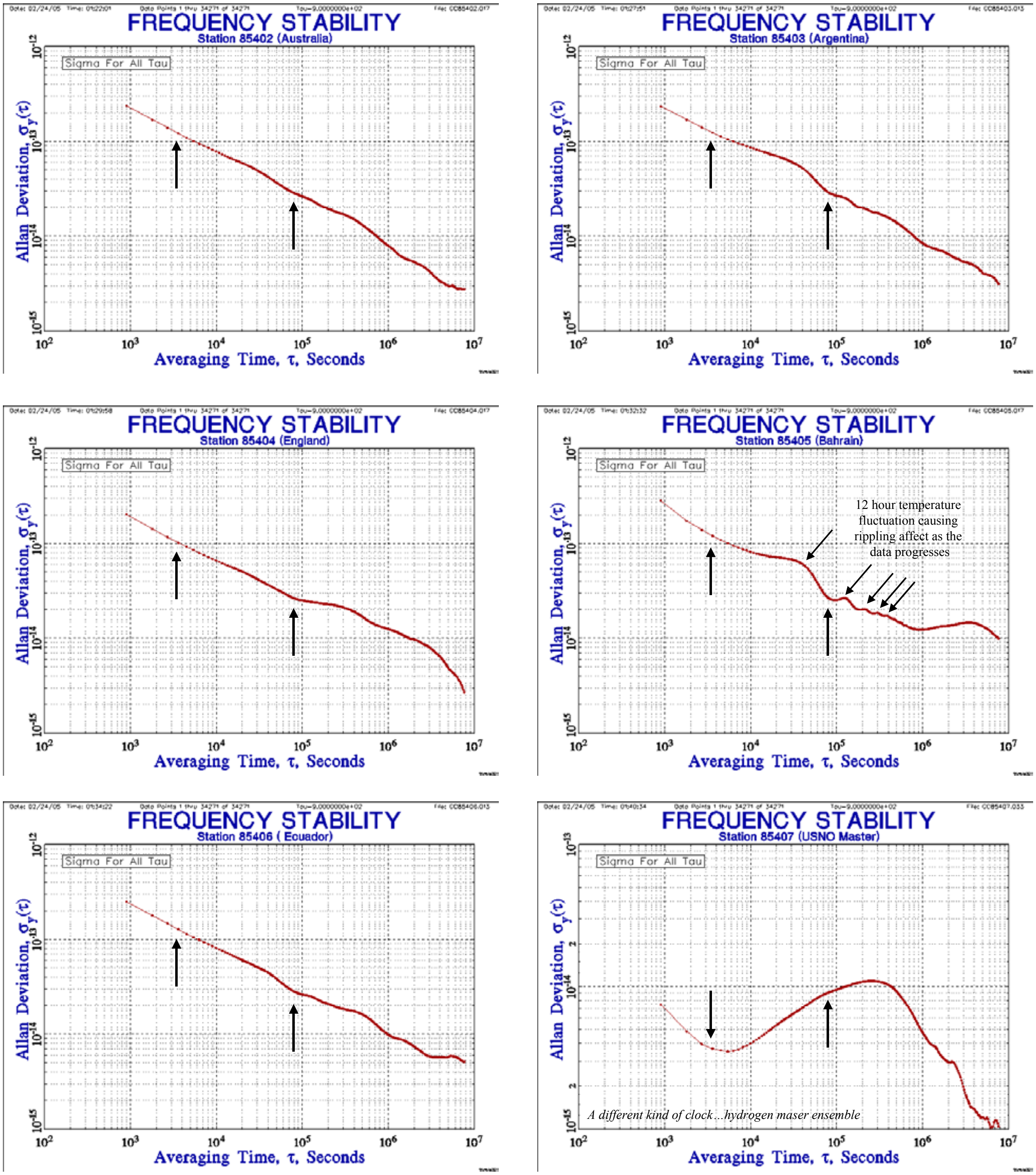


Figure 1. Frequency stability plots of the CFS at the first six NGA monitor stations. The NGA station at the USNO is tied to an ensemble of hydrogen masers. Vertical arrows are at the one-hour and one-day time locations.

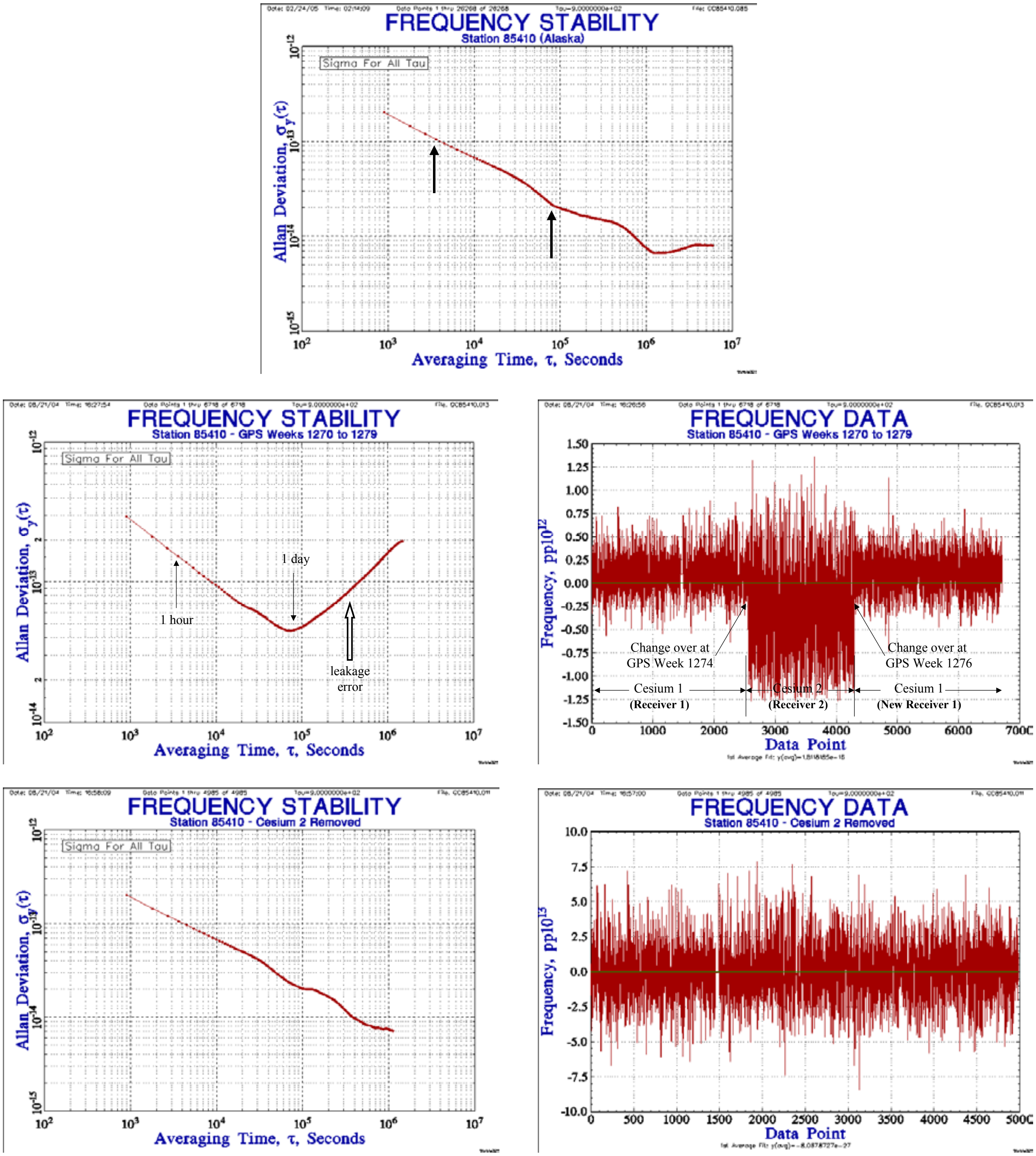


Figure 2. Frequency stability plots of the CFS at the NGA Alaskan station. Along with the yearly data are shown a clock/receiver change that caused a frequency increase. Note text for the explanation.

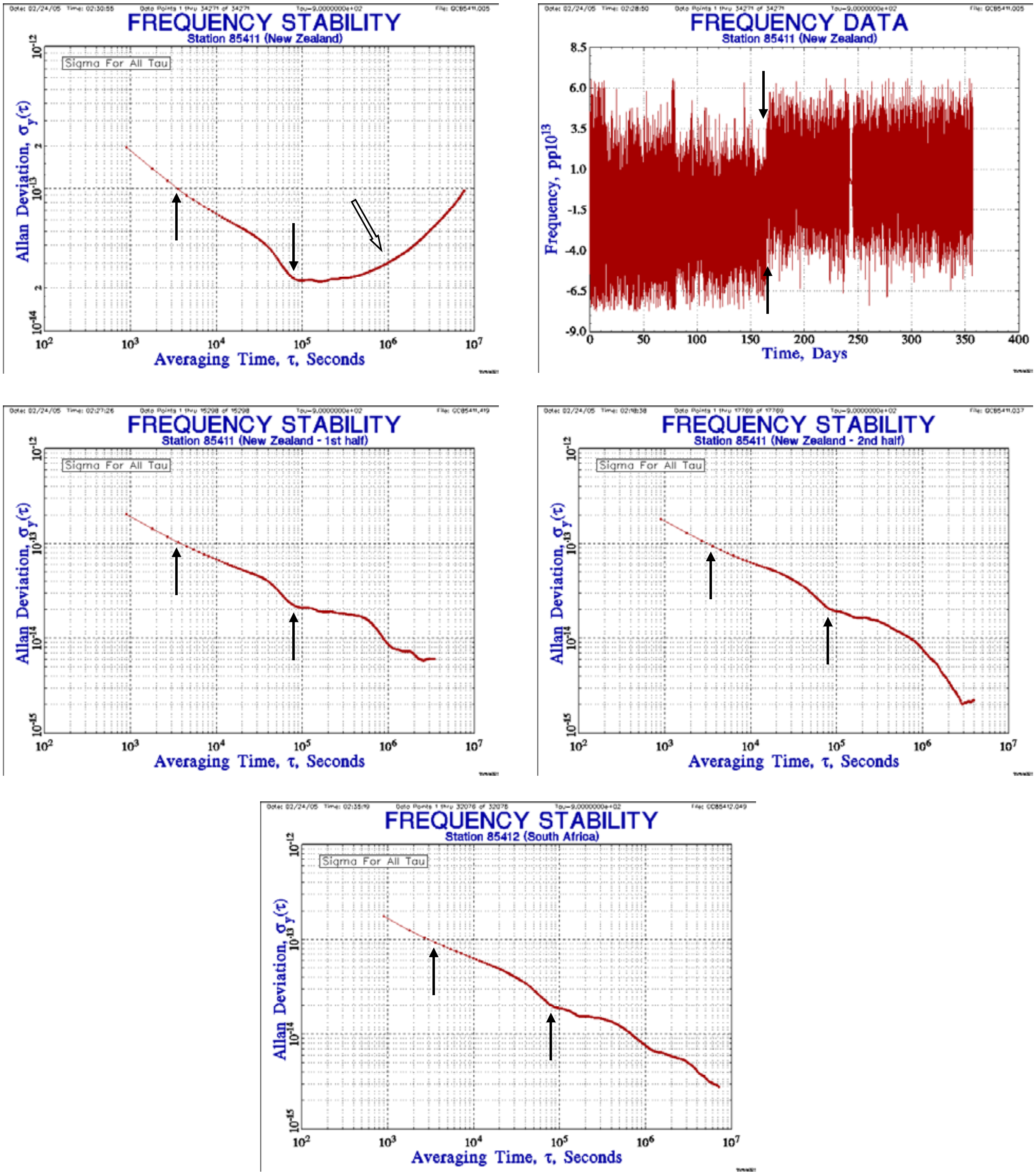


Figure 3. Frequency stability plots of the CFS at the NGA New Zealand and South Africa monitor stations. Note the frequency change due to a clock change at New Zealand. The South Africa station has shown reliable stability.

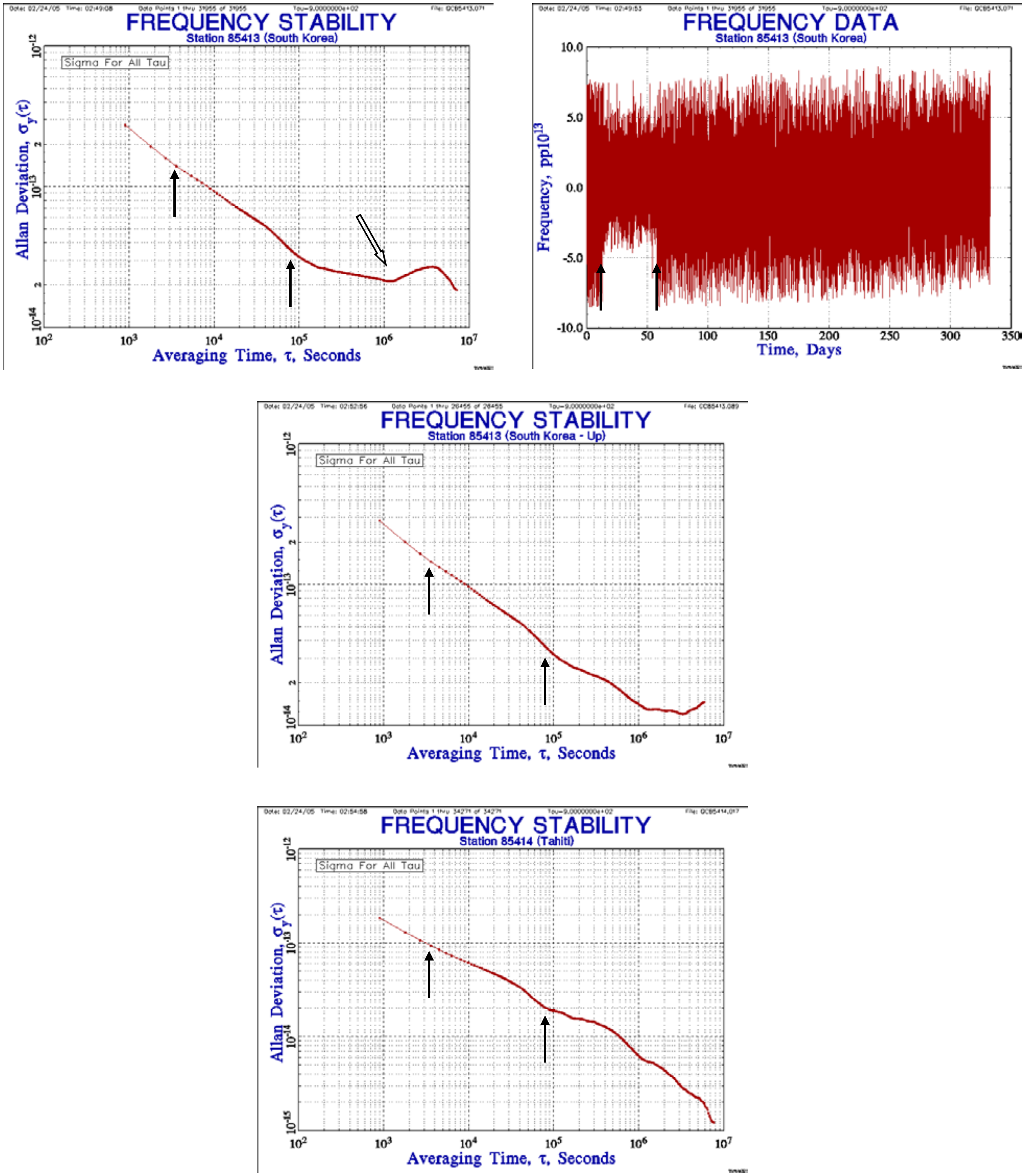
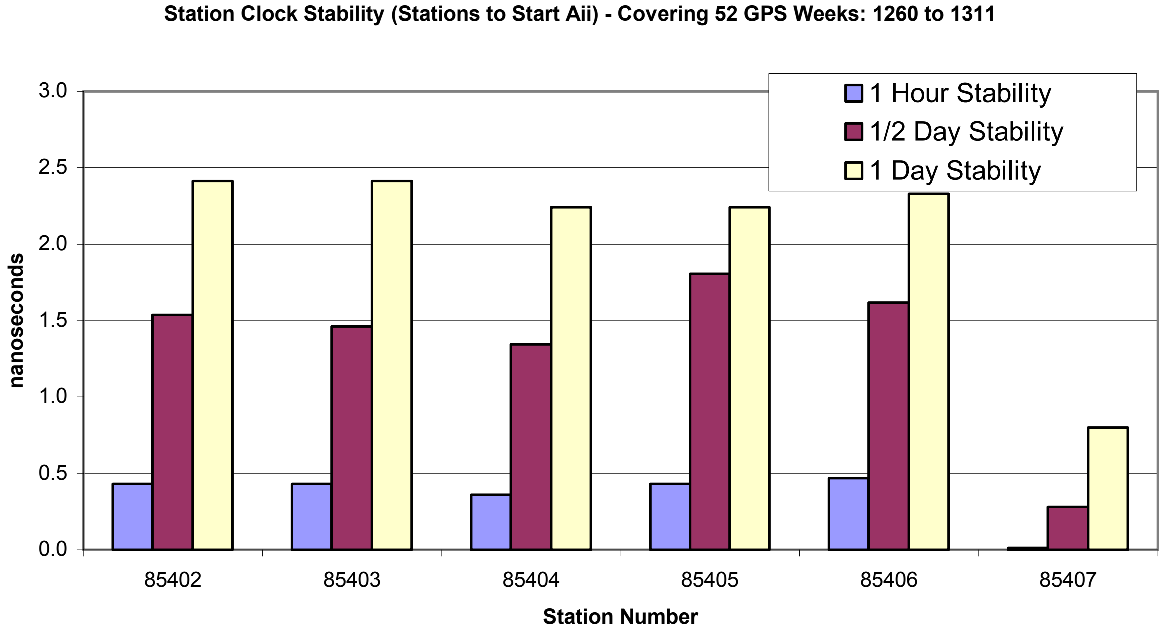


Figure 4. Frequency stability plots of the CFS at the NGA South Korea and Tahiti monitor stations. The frequency disruption shown above is due to environmental problems due to maintenance and power loss in South Korea. Note text for explanation. The Tahiti station, being the newest NGA monitor station, has shown reliable stability.



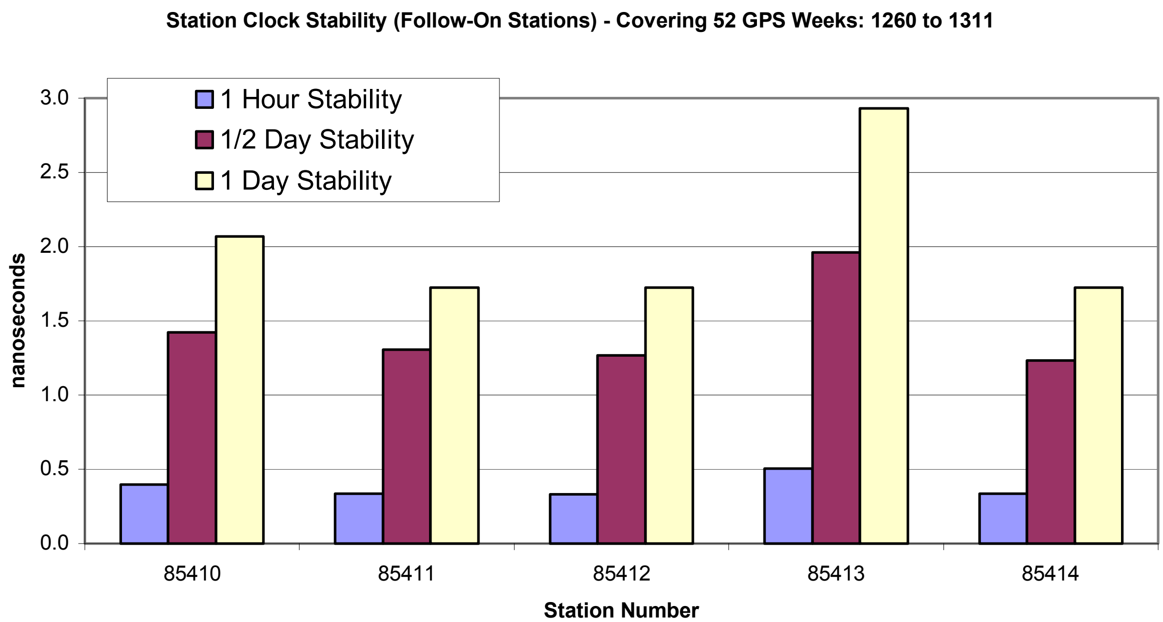


Figure 5. Station clock (frequency to time) stability of the NGA monitor stations. The top chart shows the stations to be included in the Aii process in summer of 2005. Station 85407 (USNO) statistics are much better due to the hydrogen maser ensemble. The ½ day stability statistics are used by NGA for quality control and are approximates. The station 85405 (Bahrain) shows 12-hour day-to-night temperature extremes causing higher stability values. The bottom chart shows the stations to be included in future Aii plans. The station 85413 (South Korea) has the highest values due to the numerous maintenance problems. Note text for the explanation.